Chapter 5: Introduction to Thermal Sensors and Actuators

5.1.1 Thermal Sensors Chapter 5 discusses a few key methods for measuring temperature and heat that are particularly significant in the MEMS (Micro-Electro-Mechanical Systems) field. These methods include:

1. **Thermal Bimorph Sensors** - These sensors use two layers of different materials that expand at different rates when heated, causing the sensor to bend.
2. **Thermal Couples (Thermocouples)** - These are sensors that generate a voltage related to temperature difference between two different types of metal joined together.
3. **Thermal Resistive Sensors** - These sensors change their electrical resistance with changes in temperature.

Temperature sensing is crucial not just for measuring heat but also for analyzing various physical properties and dynamics such as the distance between objects, the speed of moving media, and the characteristics of different materials.

5.1.2 Thermal Actuators Thermal actuators work by using heat to cause mechanical movements. This can be achieved through:

- **Heating** - By absorbing electromagnetic waves, electrical resistance heating (joule heating), or transferring heat from surrounding media.
- **Cooling** - Through processes like heat conduction away from the device, convection, or radiation.

A common application of thermal actuators is in inkjet printers, where heat is used to create a vapor bubble in ink to eject droplets. The process involves:

- A micro heater in a tiny fluid chamber heats the ink quickly to form a vapor bubble.
- This vapor bubble pushes out a droplet of ink.
- As the heater cools, the bubble collapses, and ink refills the chamber for the next cycle.

5.1 Introduction to Thermal Sensors and Actuators

Thermal Sensors:

- Temperature measurement can be done using various methods, particularly in MEMS (Micro-Electro-Mechanical Systems).
- Common sensors include:
    1. Thermal bimorph sensors.
    2. Thermocouples.
    3. Thermal resistive sensors.

Thermal Actuators:

- Heat changes can cause mechanical movement, which is the principle behind thermal actuators.
- A common example of thermal actuation is in inkjet printers, where heat is used to eject ink droplets from a nozzle.

5.1.3 Fundamentals of Thermal Transfer

There are four main methods of heat transfer:

1. **Conduction**: Heat moves through solid materials due to temperature differences.
2. **Natural Convection**: Heat moves from a solid surface into a still fluid (like air or water) due to buoyancy effects.
3. **Forced Convection**: Heat is transferred to a moving fluid, which enhances the transfer rate compared to natural convection.
4. **Radiation**: Heat is emitted or absorbed in the form of electromagnetic waves (e.g., heat from the sun).

5.1.2 Thermal Actuators

Actuation of microscale devices and structures can be achieved by injecting or removing heat. Changes in temperature profile in turn result in mechanical displacement or force output, through thermal expansion [5], contraction, or phase change. The temperature of a microstructure can be raised by absorption of electromagnetic waves (including light), ohmic heating (joule heating), conduction, and convection heating. Cooling can be achieved via conduction dissipation, convection dissipation, radiation dissipation, and active thermoelectric cooling.

Thermal actuation is used in commercial MEMS products. Many ink jet printers today eject ink droplets using thermal expansion of liquid inks. A schematic diagram of a single thermal ink jet printer nozzle is shown in Figure 5.1. It consists of a micromachined fluid chamber with an opening. A micro heater is embedded on the substrate within the cavity. A pulse of electrical current raises the temperature of the heater and produces a vapor bubble that squeezes the liquid ink and ejects a droplet. Upon cooling, the vapor bubble collapses and the cavity is refilled with ink again for next firing.

Due to the use of microfabrication method, the volume of ink and the thermal mass associated with the ink are small. The heating and cooling of the fluid can be performed at high speed. For many commercial ink cartridges, it takes 1 μs or less for the vapor bubble to initiate, and 15 μs for the ink to be ejected. The refill of the cavity takes approximately 24 μs.

The successful design of a reliable ink jet nozzle involves electrical, mechanical, and thermal aspects. For example, the peak pressure within the cavity can reach 14 ATM, with the peak temperature at the surface around 330°C. Both the positive and negative (cavitation) pressures are so intense that they can cause cracking of material layers over time. This warrants special design considerations. In order to eliminate cracking stemming form repeated thermal expansion and contraction, the heater is engineered from a proprietary metal oxide material that has a thermal expansion coefficient of nearly zero.

5.1.3 Fundamentals of Thermal Transfer

Temperature is manifested at the microscale by the vigorousness of atomic vibration. Heat transfer occurs whenever a temperature gradient is present in a material. Successful design of thermal actuators and sensors require familiarity with heat transfer processes.

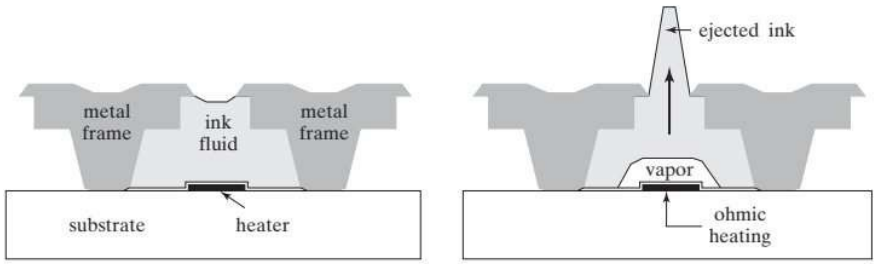

FIGURE 5.1
The principle of ink ejection.

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The following are the key heat transfer equations:

- **Conduction:** $q_{\text{cond}} = -k\frac{dT}{dx}$
- **Convection:** $q_{\text{conv}} = h(T_s - T_\infty)$
- **Radiation:** $E = \varepsilon\sigma T^4$

Here:

- kkk = thermal conductivity
- hhh = convection heat transfer coefficient

- TsT_sTs = surface temperature
- T∞T_{\infty}T∞ = surrounding fluid temperature
- ε\varepsilonε = emissivity
- σ\sigmaσ = Stefan-Boltzmann constant

Heat Transfer in Daily Life Example (Boiling Water in a Pot):

- Heat is transferred from the stove coil to the pot through conduction, from the pot wall to the water via natural convection, and from the water surface to the air via convection or radiation.

Thermal Resistance Concept:

- Thermal resistance is a measure of a material's ability to resist heat flow. The formula for conductive thermal resistance is similar to that for electrical resistance.
- $R_{\text{th}} = \frac{\Delta T}{q_{\text{cond}}} = \frac{l}{kA}$

TABLE 5.1 Typical values of convection transfer coefficients.

		$h(\text{W/m}^2 \cdot k)$
Natural convection	Gases	2–25
	Liquids	50–1000
Forced convection	Gases	25–250
	Liquids	100–20,000
Convection with phase change (boiling or condensation)		2500–100,000

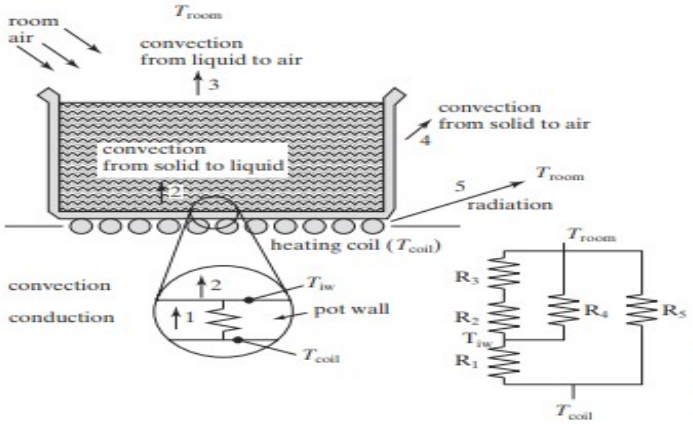
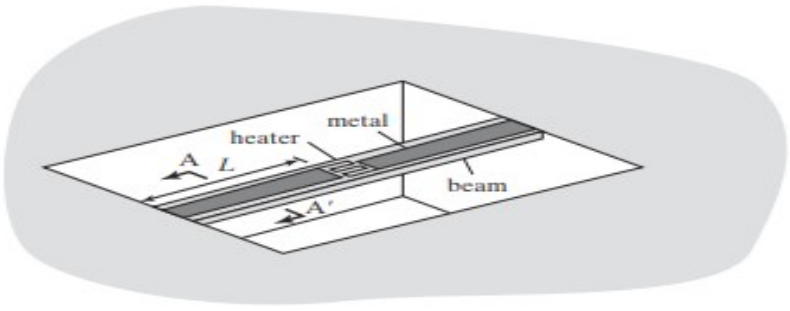
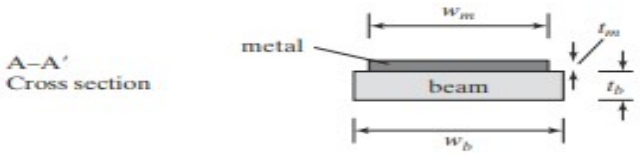


FIGURE 5.2
Heat transfer processes associated with pot heating.

Example 5.1 Thermal Resistance of Suspended Bridge

A resistive ohmic heater is located in the middle of a suspended fixed-fixed cantilever. The beam is made of silicon nitride and the metal leads are made of aluminum. Find the numerical value of the thermal resistance experienced by the heater. Assume the width of the beam is 10 μm, $L = 100\,\mu$m, and the thickness of both aluminum (t_m) and silicon nitride (t_b) is 0.2 μm. If the input power to the heater is 0.1 mW, what is the steady temperature assuming the silicon bulk stays at 27°C?





Problem Statement
You have a beam designed like a cantilever (a beam fixed at one end and free at the other). This beam has a heater placed in the middle. It's made of silicon nitride with aluminum leads. The task is to calculate how much resistance this beam provides against the flow of heat from the heater.

Given Data

- The beam is made from two materials: silicon nitride and aluminum.
- Thermal conductivity of aluminum: $240\ \mathrm{W/mK}$
- Thermal conductivity of silicon nitride: $5\ \mathrm{W/mK}$
- Power of the heater: $0.1\ \mathrm{mW}$ (This is how much heat the heater is putting out.)
- The thermal resistance tells you how hard it is for heat to travel through materials.

Steps to Solve

1. **Calculate the Thermal Resistance for Each Material:** The formula used is based on the material's properties (like its thermal conductivity), its dimensions (how thick and wide it is), and how long the heat needs to travel through it.
   - For aluminum (metal part of the beam):
   $$R_m = \frac{L}{\kappa_m W_m t_m} = \frac{200 \times 10^{-6}}{240 \times 0.2 \times 10^{-2} \times 10^{-12}} = 4.17 \times 10^5\ \mathrm{K/W}$$
   - For silicon nitride (beam itself):
   $$R_{SiN} = \frac{L}{\kappa_{SiN} W_{SiN} t_{SiN}} = \frac{200 \times 10^{-6}}{5 \times 0.2 \times 10^{-2} \times 10^{-12}} = 2 \times 10^7\ \mathrm{K/W}$$
2. **Combine the Resistances:** Since the heater is connected to both types of materials and they are arranged to carry heat away from the heater in parallel, you combine these resistances using the formula for combining parallel resistors:
   $$\frac{1}{R} = \frac{1}{R_m} + \frac{1}{R_{SiN}} \Rightarrow R = \frac{1}{\frac{2}{R_m} + \frac{2}{R_{SiN}}}$$
   - Plug in the calculated resistances to find the total resistance R.
3. **Find the Temperature Difference:** Using the power of the heater and the total resistance, you can find how much the temperature rises from the base (ambient) temperature using the formula $\Delta T = R \times \mathrm{Power}$.

Result
The calculated thermal resistance tells us how effectively the beam resists the flow of heat from the heater to its surroundings. The lower the resistance, the more easily heat escapes, and vice versa. By calculating ΔT\Delta TΔT, we can see how much the temperature at the heater will rise above the ambient temperature due to its operation. This is crucial for understanding how much cooling might be necessary or what material properties are required to ensure the device operates safely and efficiently.
technologies:

1. **Thermal Resistance and Speed of Temperature Change in Microstructures**:
   - The speed at which microstructures (like parts of a microsensor or microactuator) can heat up or cool down is very important. For example, the heating and cooling rates of a part in an inkjet printer affect how fast the printer can operate.
   - The thermal resistance, or the material's resistance to heat flow, impacts how quickly temperature changes occur within these structures.

    - Stored thermal energy and temperature change are related through specific heat (the amount of heat per unit mass required to raise the temperature by one degree) and heat capacity (similar to electrical capacitance but for thermal energy).
2. **Thermal Expansion in Materials**:
    - Thermal expansion is when materials expand in volume or dimensions as they heat up. This is common in metals, semiconductors, and dielectrics.
    - The volumetric thermal expansion coefficient (TCE) measures how much the volume of a material changes relative to temperature change.
    - The linear expansion coefficient measures how much one dimension of an object changes with temperature.
3. **Application of Thermal Expansion**:
    - Devices such as thermal bimorph actuators use materials with different expansion rates to create movement from heat changes.
    - Air trapped in microfluidic devices can expand with heat to move liquids or generate pressure.
4. **Thermal Properties of Materials**:
    - Materials have specific thermal properties like conductivity and expansion coefficients that influence how they behave in thermal applications.
    - Data on these properties vary widely and are influenced by the material's composition and processing history.
5. **Use of Thermal Expansion in MEMS**:
    - Thermal expansion properties allow for the design of actuators that operate on the expansion of liquids or gases, which can be significantly greater than those of solids.
    - The properties of air, when heated, can be used to manipulate small volumes of liquid in microfluidic devices, demonstrating practical applications of thermal expansion.

Thermal Bimorph Principle

What is Thermal Bimorph?

- A thermal bimorph is a type of sensor or actuator that responds to changes in temperature. It consists of two materials bonded together that expand at different rates when heated.

How Does it Work?

- Each material in a bimorph has its own rate of expansion when heated, known as the Coefficient of Thermal Expansion (CTE).
- When the temperature changes, the difference in expansion rates causes the bimorph to bend. The material with the lower CTE bends towards the one with the higher CTE.

Composition and Behavior:

- Typically, a bimorph will consist of two layers of materials such as metals or semiconductors.
- These materials are joined lengthwise but expand differently as the temperature changes.
- The bending occurs because one layer expands more than the other due to its higher CTE, forcing the entire structure to curve.

Calculating the Bend:

- The bending or curvature of the bimorph is calculated using specific material properties like Young's modulus (stiffness), width, and thickness, as well as their respective CTEs.
- The formula for calculating the radius of curvature takes into account these properties and the change in temperature.

Practical Application:

- When a bimorph bends, it can move other mechanical components or act as a switch or sensor by changing its position relative to other parts of a device.
- This bending movement can be precisely calculated to activate mechanical movements in response to temperature changes.

Visual Explanation:

- The provided diagrams illustrate how a straight bimorph bends into an arc when heated. This bending is depicted by comparing the original straight position to the curved position after heating.

Understanding the Bend and Displacement:

- Once the radius of the bend is known, you can determine how much the end of the bimorph has moved from its original position. This movement, or displacement, is critical for applications like precise actuation in microdevices.

Thermal Bimetallic Actuation: Thermal bimetallic actuation uses two different metals bonded together. When heated, these metals expand at different rates, causing the device to bend or move. This movement can be used to turn devices on or off, like in some thermostats.

Application in Thermostats: Many household thermostats use a coiled metal strip made from two different metals. This strip is connected to an electrical circuit that contains a mercury switch. When the room temperature changes, the metal strip bends and tilts the mercury switch. This tilting turns the heating or cooling system on or off, helping maintain the desired room temperature.

Comparison with Electrostatic Actuation:

- **Electrostatic Actuation:** Uses electrical charge to create movement. It's effective at low power and can react quickly, but it can only move very small distances and might need a large area to work effectively.
- **Thermal Bimetallic Actuation:** Can create larger movements and fit into small spaces compared to electrostatic methods. However, it needs more power and responds more slowly because it works by heating and cooling.

Examples in Microengineering: Thermal bimetallic actuators are explored in micromachines, where they move tiny objects. Some designs are simple and don't use electronics, while others include integrated circuits to control the movement more precisely.

Electrostatic Actuation:

- **Advantages:**
    1. **Low Power Operation:** It works well at low power levels, making it energy-efficient.
    2. **High Response Speed:** It reacts very quickly, which is beneficial for applications that require fast movement.
- **Disadvantages:**
    1. **Small Range of Motion:** It can only move very short distances, which limits its use in applications requiring larger movements.
    2. **Large Area Requirement:** It needs a large surface area to function effectively, which can be a limitation in compact devices.

Thermal Bimetallic Actuation:

- **Advantages:**
    1. **Large Range of Movement:** It can produce a significantly larger movement compared to electrostatic actuators, which is useful in various mechanical applications.
    2. **Small Actuator Footprint:** It can achieve considerable movements without needing a lot of space, making it suitable for compact designs.
- **Disadvantages:**
    1. **Higher Power Needs:** It requires more energy, often in the form of heat, which might not be ideal for all applications.
    2. **Slower Response:** The actuator responds more slowly than electrostatic types because the speed of response is limited by how quickly it can heat up or cool down.

Problem 3: Design

A bimetallic cantilever beam is made of two components with same length. The material on top (denoted Material 2) is gold, whereas the materials on the bottom (Material 1) is SCS (single-crystal silicon). The width of both segments is 10 μm. The length of both segments is 1 mm. The Young's modulus of Gold and Si are $E_2 = 57$ GPa and $E_1 = 150$ GPa, respectively. The thickness of Gold and Silicon sections is $t_2 = 0.5$ μm and $t_1 = 1.5$ μm, respectively. The thermal expansion coefficients of Gold and Silicon is $\alpha_2 = 14$ ppm/°C and $\alpha_1 = 2.33$ ppm/°C, respectively. Find the radius of curvature (r) of the cantilever beam when the beam is uniformly heated to 20°C above the room temperature. Determine the amount of vertical displacement at the free end of the beam under this condition.

1. **Given data:**
   - L (Length of both segments): 1 mm
   - w (Width of both segments): 10 µm
   - $E_{\text{gold}} = 57 \text{ GPa}$
   - $E_{\text{Si}} = 150 \text{ GPa}$
   - $t_{\text{gold}} = 0.5 \text{ µm}$
   - $t_{\text{Si}} = 1.5 \text{ µm}$
   - $\alpha_{\text{gold}} = 14 \text{ ppm}/^\circ\text{C}$
   - $\alpha_{\text{Si}} = 2.33 \text{ ppm}/^\circ\text{C}$
   - Temperature rise (ΔT): 20°C
2. **Calculations for Radius of Curvature (r):**
   - Formula:

$$\frac{1}{r} = \frac{6w_1w_2E_1E_2(t_1+t_2)(\alpha_1-\alpha_2)\Delta T}{w_1E_1t_1^2 + w_2E_2t_2^2 + 2w_1w_2E_1E_2t_1t_2(3t_1+3t_2)}$$

Substitute the given values:

- $w_1 = w_2 = 10 \times 10^{-6} \text{ m}$ (converted from µm)
- $t_1 = 0.5 \times 10^{-6} \text{ m}, t_2 = 1.5 \times 10^{-6} \text{ m}$
- $\alpha_1 = 14 \times 10^{-6} /^\circ\text{C}, \alpha_2 = 2.33 \times 10^{-6} /^\circ\text{C}$

$$\frac{1}{r} = \frac{6 \times 10^{-5} \times 10^{-5} \times 57 \times 10^9 \times 150 \times 10^9 \times (0.5 \times 10^{-6} + 1.5 \times 10^{-6}) \times (14 \times 10^{-6} - 2.33 \times 10^{-6})}{10^{-5} \times 57 \times 10^9 \times (0.5 \times 10^{-6})^2 + 10^{-5} \times 150 \times 10^9 \times (1.5 \times 10^{-6})^2 + 2 \times 10^{-5} \times 57 \times 10^9 \times 150 \times 10^9 \times 0.5 \times 10^{-6} \times 1.5 \times 10^{-6}}$$

$$\frac{20}{(3 \times 0.5 \times 10^{-6} + 3 \times 1.5 \times 10^{-6})}$$

3. **Vertical Displacement (d):**
   - Use the geometry of the bending beam to find vertical displacement:

$$d = r - r\cos(\theta)$$

   - Where θ is the bending angle, approximated as $\theta \approx \frac{L}{r}$
   - For small angles, $\cos(\theta) \approx 1 - \frac{\theta^2}{2}$, hence:

$$d \approx r\left(1 - \left(1 - \frac{1}{2}\left(\frac{L}{r}\right)^2\right)\right) = \frac{L^2}{2r}$$

The calculated radius of curvature (r) of the bimetallic cantilever beam, when uniformly heated to 20°C above the room temperature, is approximately $213,572,709$ meters, which indicates an extremely large radius suggesting very slight curvature.